

NASA/TM—2016–219426



Anthropomorphic Robot Design and User Interaction Associated with Motion

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November 2016

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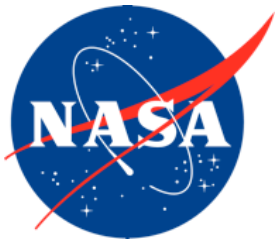
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Acronyms and Definitions

DARPA	Defense Advanced Research Projects Agency
EVA	extravehicular activity
G	gravity
HARI.....	Human and Automation/Robotic Integration
HMD	head-mounted display
JPL	Jet Propulsion Laboratory
MIT	Massachusetts Institute of Technology
ms	milliseconds
NASA	National Aeronautics and Space Administration
TOPS.....	Navy Teleoperate System
VIVED	Virtual Visual Environment Display

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Stephen R. Ellis¹

Executive Summary

Though in its original concept a robot was conceived to have some human-like shape, most robots now in use have specific industrial purposes and do not closely resemble humans. Nevertheless, robots that resemble human form in some way have continued to be introduced. They are called anthropomorphic robots.

The fact that the user interface to all robots is now highly mediated means that the form of the user interface is not necessarily connected to the robot's form, human or other-wise. Consequently, the unique way the design of anthropomorphic robots affects their user interaction is through their general appearance and the way they move. These robots' human-like appearance acts as a kind of generalized predictor that gives its operators, and those with whom they may directly work, the expectation that they will behave to some extent like a human. This expectation is especially prominent for interactions with "social robots," which are built to enhance it. Often interaction with them may be mainly cognitive because they are not necessarily kinematically intricate enough for complex physical interaction. Their body movement, for example, may be limited to simple wheeled locomotion.

An anthropomorphic robot with human form, however, can be kinematically complex and designed, for example, to reproduce the details of human limb, torso, and head movement. Because of the mediated nature of robot control, there remains in general no necessary connection between the specific form of user interface and the anthropomorphic form of the robot. But their anthropomorphic kinematics and dynamics imply that the impact of their design shows up in the way the robot moves.

The central finding of this report is that the control of this motion is a basic design element through which the anthropomorphic form can affect user interaction. In particular, designers of anthropomorphic robots can take advantage of the inherent human-like movement to: 1) improve the users' direct manual control over robot limbs and body positions; 2) improve users' ability to detect anomalous robot behavior which could signal malfunction; and 3) enable users to be better able to infer the intent of robot movement.

These three benefits of anthropomorphic design are inherent implications of the anthropomorphic form but they need to be recognized by designers as part of anthropomorphic design and explicitly

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enhanced to maximize their beneficial impact. Examples of such enhancements are provided in this report. If implemented, these benefits of anthropomorphic design can help reduce the risk of “Inadequate Design of Human and Automation/Robotic Integration” (HARI) associated with the HARI-01 gap by providing efficient and dexterous operator control over robots and by improving operator ability to detect malfunctions and understand the intention of robot movement.

1. Introduction

Because of the need to maximally extend the benefits of human presence during crewed deep space planetary exploration, all such National Aeronautics and Space Administration (NASA) design reference missions include robots of a wide variety which are intended to interact with the crew. The form-factor of those that will interact only episodically, briefly, and largely through the interface of a scripting or programming language will largely be determined by the task and the constraints of the physical environment. Those that interact frequently, for extended times, and possibly through direct physical contact, introduce additional design constraints that include the physical appearance of the robot, and in particular include the possibility that the robot takes on a human-like form. Such human-like robots are described as anthropomorphic and NASA has already been explicitly designing one called Robonaut. The following paper discusses some of the ways anthropomorphic form can influence user interaction with robots.

During the past approximately 30 years, robot technologists have been developing and fielding a series of anthropomorphic robots for a variety of uses ranging from entertainment, underwater salvage, robot-based surgery, to space exploration (Hollerbach & Jacobsen, 1996; Adams, Breazeal, Brooks & Scassellati, 2000). Most recently, anthropomorphic robots have been challenged by Defense Advanced Research Projects Agency (DARPA) to demonstrate very generic human behaviors such as entering a car or using a handle to turn off a valve.

The presumption of these most recent challenges seems to be that robots with generic behavioral capabilities can reveal the driving problems that will advance robotics as a field and perhaps create a single system that can have multiple roles such as bomb deactivation, search and rescue in cluttered environments, and perhaps provide a general purpose replacement for a foot soldier (Guizzo & Ackerman, 2015).

Anthropomorphic robots exhibit a unique form of embodied automation and autonomy that makes them distinct from typical automation and robots because of their human-like form. This difference impacts the discussion of the performance requirements for human-robotic interaction, not only because of the robots’ form and consequent human-like motion, but also because they are also intended for tasks in an environment in which they will closely, and frequently physically, interact with their human operators and other humans for whom they will act as assistants. A reading of literature on the topic of anthropomorphic robots shows that there are three system characteristics that distinguish user interactions with anthropomorphic robots from other forms of robots and that these characteristics can be the basis for improved human-robot interaction.

The three system characteristics identified are: *intuitive control*, *sensitive anomaly detection*, and *intent² predictability*. After a brief review of what an anthropomorphic robot is and illustration of several examples, these three system characteristics will be described, their importance justified, and some of their relations to user experience and user interfaces discussed. The first of these three characteristics is connected to the geometry and dynamics of how anthropomorphic robots move. The second two—while also being associated with robot motion—essentially involve nonverbal communication between the robot and its operator or humans working along side it. Specific design enhancements illustrating these system characteristics will be proposed in terms of Robonaut, a series of robots NASA is developing for space exploration. Robonaut serves as a particularly good example for illustrating these three system characteristics because it is intended to be used in the three classical robot control modes as identified by Sheridan (1992): 1) a teleoperator under essentially continuous manual control; 2) a telerobot under intermittent manual control; or 3) a fully automatic robot running autonomously for extended time periods.

2. What is an Anthropomorphic Robot?

A robot may be defined after Sheridan as a “reprogrammable, multifunctional manipulator designed to move material parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks” (Sheridan, 1992, pp. 3–4). Robots are popularly thought to closely resemble a human form but in fact most robots are in industrial use and do not closely resemble humans in form or function (Figure 1).



Figure 1. A nonanthropomorphic industrial robot being programmed by an interactive technique in which it is manually moved through a sequence of recorded positions for programmatic playback. Though human instructors may interact closely with the robot during instruction, being close to an industrial robot during actual operation is dangerous. They are typically operated away from human contact. Contemporary anthropomorphic robots are much more likely than industrial robots to interact physically with operators and observers during normal operation.

² The following paper primarily refers to what has been called low level intentionality (L-intentionality) indicated by the homing evident in the goal seeking behavior. “Low level intentionality is attributed when an agent has a theory of mind for another agent. High level intentional is attributed when an agent believes another has a theory of mind for something else” (Admoni & Scassellati, 2012). If I see a monkey chasing another away to defend some food it caught, the chasing monkey is exhibiting low level intentionality. However, if I see the intruding monkey camouflaging itself to get a better shot at stealing the food, the intruder would be exhibiting high level intentionality.

Before describing Robonaut, it is helpful to consider why any inventor would even consider an anthropomorphic design for a robot. There is nothing inherent in the Sheridan definition of a robot that skews design in an anthropomorphic direction. But if one thinks further that the operators and those working in close proximity to the robot might share tools and tasks, the situation changes. In fact, this kind of close human robot collaboration is envisioned for deep space exploration as a way to decrease the amount of extravehicular activity (EVA) time required of human crew and minimize the mass required.

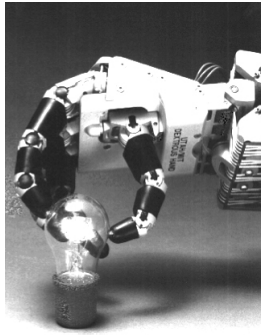
If the designer expects such frequent and close interaction as suggested by many use cases, e.g., cooperative construction, sample retrieval, mechanical repair, etc., it becomes especially important for the operators as well as other crew who would collaborate physically nearby the robot to have a current, accurate, and complete understanding of what the robot is doing and why. This requirement is not particularly unique for robotics since it equally well could apply to other types of automation. But the close interaction raises significant safety risks. Any robot strong enough to be useful is also strong enough to be dangerous. A robot having anthropomorphic form has the advantage of making it possible for robot operators and companions to use their intuitions regarding human behavior and interaction as a way to understand the movement of the robot, its current internal status, and its likely future activity. In fact, the anthropomorphic form itself facilitates a kind of generalized, intuitive prediction about the robot's capacities. These intuitions can, in fact, be helpful. The enhancements discussed below propose ways to use or extend them.

On the other hand, if the robot cannot live up to the intuitive expectations, these intuitions can themselves cause problems. This issue has already been reported for anthropomorphic service robots designed to help the elderly (Tondur, 2012). The negative effect of a mismatch between expectation and reality for anthropomorphic can be particularly aggravated because these systems inherently can produce affective responses, e.g., anger, distrust, from their operators and companions. Researchers have argued that this affect can influence acceptance and utilization of anthropomorphic robots (Maya & Reichling, 2009). This affective response may well be based on more than just personal experience with the robot but also something resembling what Hoff and Bashir (2015) called the "dispositional trust" that humans bring to the interaction with the robot. The violation of this implicit trust could be the source of the negative affect.

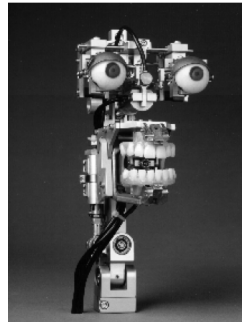
3. Examples of Anthropomorphic Robots

The range of robots that can be considered anthropomorphic has been clearly established by a review that is arguably a founding document by pioneers in the field (Hollerbach & Jacobsen, 1996). Figure 2 from their paper titled "Anthropomorphic Robots and Human Interaction" shows the range of robots that fit within the field³.

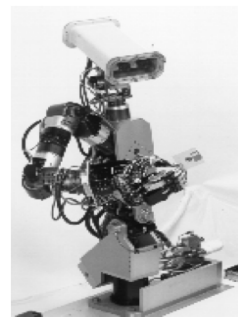
³ The terms anthropomorphic and humanoid are not used consistently, even within the same paper, but there seems a slight preference for humanoid when the geometric linkage is not the central concern of the developer or researcher.



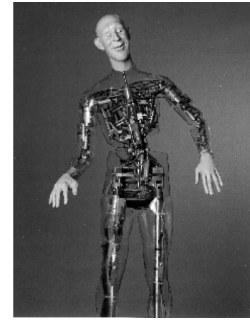
The Utah/MIT Dexterous Hand, a 4-fingered hand driven by a 4-fingered hand master (not shown).



A Disney robot for facial animation which in operation would be enclosed in a full head model.



The slave robot for the Navy Teleoperate System (TOPS) built by Sarcos.



A fully embodied Disney robot for character animation. In operation, it would be fully clothed.

Figure 2. The range of anthropomorphic robots from articulated arms to fully embodied examples with human-like torso, limbs, and hands. From Hollerbach and Jacobsen (1996).

Table 1, and especially Figure 2, identify that this class of robots ranges from articulated arms with hand-like effectors through fully embodied robots that may add mobility systems such as legs. Some examples additionally have internally animated, expressive faces, skin covered limbs, and anatomically realistic hands. At this high end of realism, the robots have all the external structures to mimic human expression and connote emotion. They are intended to, and can succeed in, triggering emotional reactions in those who might view them. This fact is important because it distinguishes them from other examples of automation and robotics. Moreover, while the anthropomorphic form may not itself be the design goal but only a consequence of other design considerations, affect can be a potentially uncontrolled and significant side effect.

Table 1. A collection of robot devices of various sort described as anthropomorphic robots by Hollerbach and Jacobsen (1996)

Humanoid Robot	Sponsor Goals	Technology Push
Utah Artificial Arm	Myoelectric prosthetic arm	EMG-based control, impedance control
Sarcos AdVAntage Arm	Passive or active prosthetic arm	Independent elbow, terminus control
Disney robots	Many DOFs, high performance	Aesthetic motion, shape and color
Utah/MIT Dexterous Hand	Advanced hand for dexterity research	High functionality, antagonistic actuation, analog controller, Condor
Utah Dexterous Hand Master	Teleoperation of hand	Accurate measurement of angles
Tactile sensors	Complete sensing for hand	Robust, accurate system design
Navy Teleoperated System	Submersible, high DOFs, force-reflecting	High-performance actuation, Advanced Joint Controller
Sarcos Dexterous Arm Slave	Commercialization of Navy system	High-bandwidth force and position control
GRLA	Power-line maintenance	First art-to-part product
Morph hand	Reconfigurable vise or finger gripper	Adaptability to tasks
Sarcos Dexterous Arm Master	Force-reflecting exoskeleton for slave	Ergonomics, gravity compensation
Ford robot	Human-controllable display robot	Portability mobility
Sensor suit	Whole-body goniometer	Fit, calibration, DOFs
Jurassic Park Dinosaurs	Realistic, high-performance figures	Art-to-part large designs, Digital Controller
Human emulation technology	Spacesuit testing	Human body emulation, measurement

It is important to note that the source of affect is not solely in the facial and body detail, gestures, and poses; affect can come through the patterns of motion itself. For example, it is known that complex human affect can be attributed even to simple geometric forms in complex motion. This phenomenon has been studied in terms of what is called “Attribution Theory” since Heider and Simmel first examined it (1944 *et sequalia*). The power of the motion of abstract shapes to elicit human emotion may not be surprising to animators who have daily use for this fact (Ratner, 2012, p. 357) and who have also shown that the evocative effect of the motion can be independent of the shapes that carry it (McDonnell et al, 2008). As will be discussed below, the pattern of motion itself can be a design element and can trigger sometimes unintended and unexpected affect.

Figure 2 also includes examples of what could be called a social robot, i.e., the fully embodied Disney robot (far right), designed to be visually almost indistinguishable from an actual person when clothed. This robot was explicitly intended to evoke affect. The Disney robots were and continue to be designed to create the illusion of interaction with a fully intelligent human agent. The illusion can be created either by placing careful constraints on the allowed interaction or by the use the Wizard-of-Oz control technique (Reik, 2012). Wizard-of-Oz control is a kind of puppeteering in which operators, often several working simultaneously, teleoperate the many degrees of freedom of a robot and sometimes speak through it to a human companion. Wizard-of Oz control to some extent resembles NASA control of a robot spacecraft in that a number of people, each of whom is specialized in one type of vehicle operation, collaborate in a control room to operate a remote vehicle. One purpose of social robotics is to simulate and investigate intelligent interactions that are not now possible between humans and robot assistants but which one day might be realized when robots are more fully intellectually capable. Because the aim of this realization may not necessarily be complex physical interaction, the social robots need not be kinematically complex. They may, for example, only have simple wheeled locomotion or simple animated faces as in Figure 3. But it is important to remember that no matter how simple a robot may appear, once it generally is seen to resemble a human, user interaction with it is almost inevitably somewhat social.

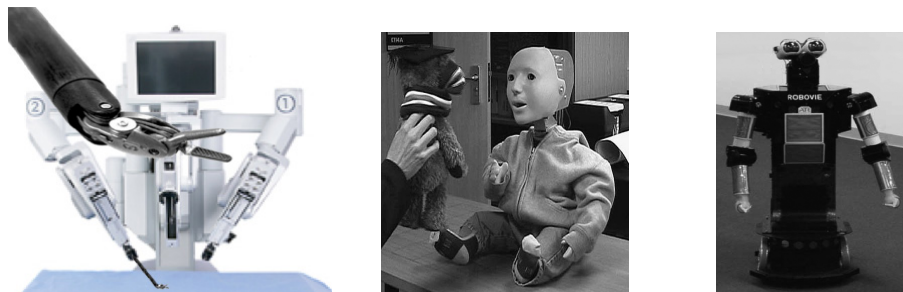


Figure 3. Left: The first commercial da Vinci[®] surgical robot manipulator and an enlarged example of a special purpose tool illustrating its wrist, which is a key kinematic feature that contributes to the systems high dexterity. Middle: A stationary social robot with a curiously blank, somewhat disturbing facial expression (Dautenhahn, 2007). Right: A simple wheeled robot originally introduced to support simple social interaction such as turn taking (Imai, Ono & Ishiguro, 2002).

Figure 3 shows three more recent robot examples. Intuitive Surgical’s da Vinci[®] medical robot on the left (Guthart & Salisbury, 2000) is anthropomorphic particularly because of its introduction of a wrist joint that provides degrees of control freedom similar to a human wrist. This robot is significant not only because it has established a state of the art for teleoperator dexterity but because

it is used worldwide with over 3,100 units in the field. The very substantial progress made in surgical robotics suggests that remote surgery may well become feasible in NASA environments for which communication latency is very low (~20 ms). Clearly, this does not include deep-space crewed missions if the surgical teleoperator is conventionally controlled from afar. However, as discussed below, a predictive display technique may well be useable to compensate for some long delays, particularly if it is assisted by highly accurate real-time 3-D surface capture of the surgical site and machine-vision guided execution of surgeon-generated movements.

The social robot shown in the middle of Figure 3 illustrates the kind of visual “creepiness” that can be encountered when robots begin to approach human form but don’t quite make it all the way. This phenomenon, which also can be triggered by movement that is not quite human, is known as the “Uncanny Valley” after analysis by Mori⁴. It influences user acceptance of robots by operators or by those who might be physically collaborating with them and it actually has been reported with respect to limb movement which seemed eerie during testing and development of Robonaut, the NASA anthropomorphic robot (Rochlis, 2015). The “creepiness” arising from the Uncanny Valley is important to note during robot development because its effects can arise inadvertently if design influences lead in an increasingly anthropometric direction. In fact, this caution applies to the NASA Robonaut robot which is evolving in an anthropomorphic direction because of a decision for it to use human tools and move about spacecraft as the human crew does.

Some of the most recent examples of anthropomorphic robots can be found in reports on the 2015 annual DARPA Robotics Challenge, an event intended to showcase the most current robotics technology and to advance it. Development groups are invited to demonstrate how well and how fast their newly designed robots can accomplish a wide variety of challenging tasks commonly accomplished by humans. Because these tasks are not precisely described in advance, the robots entered into the challenge tend to be somewhat general purpose, a fact that encourages anthropomorphic designs. Interestingly, the most successful entries in the latest contest seem to have succeeded by avoiding a major anthropomorphic feature: bipedal walking. Bipedal locomotion was until recently (Ackerman & Guizzo, 2016) beyond current control technology because it is very sensitive to incorrectly sensed environment conditions such that small errors can lead to catastrophic failures (Figure 4, Guizzo & Ackerman, 2015).

⁴ This term refers to an observer’s sense of revulsion, or perhaps just emotional disturbance, when viewing robots that closely, but not quite completely, approach visual or kinematic human likeness. When the robots are close to human form and movement, slight changes in appearance or motion produce large changes in observer reactions (Mori, 1970, 2012, 2012a *et sequelae*; Pollick, 2009). This effect has also been studied with respect to robots as well as realistically rendered human avatars. It could be related to the known sensitivity of observers for discriminating changes in kinematically realistic biological motion from biologically unrealistic motion (see Bidet-Ildei & Orliaguet, 2006 for a representative experiment with a good bibliography).



Figure 4. A fallen robot at the 2015 DARPA Robot Challenge.

4. Coherence of Anthropomorphic Robot Design Elements

It is difficult to make generalizations regarding the impact of anthropomorphic robot design on conventional human-robot interfaces for two reasons. One is that the superficial, human-like appearance of the robot does not necessarily determine the form of the users' control interface. The design of the user interface can be made independent of the robot's design itself. Moreover, the anthropomorphic form of the robot most directly affects the robot's physical interface to the world—not its operator's interface to the robot. However, some forms of direct manipulative control are conceptually easier to implement with anthropomorphic systems, as discussed below in the section on Intuitive Control. However, forms of intuitive control can also be implemented in user interfaces to nonanthropomorphic systems.

A second reason generalizations are difficult is that these robots can be very diverse. Robots may look, act, or simply move like a human but may not be driven through user interfaces well matched to the robots' kinematics. Robots may be used to accomplish complex mechanical tasks under teleoperation or they may be used to investigate social interaction at the highest cognitive level by using extremely simple locomotion and limb movement. In some forms that arguably are in fact anthropomorphic robots, the exoskeletons sometime called man-amplifiers (e.g., Kazerooni & Steger, 2005), robot actuators and the user interface are actually physically coincident! In fact, the outward human shape of the most typical anthropomorphic robots and possible use cases can encourage their operators to interact with them both through direct physical contact as well as through a conventional interface such a joystick. Their operators thus may even be concurrently using two different interfaces.

Nevertheless, though it is a little like understanding how the shape of a cheese package may affect the taste of the cheese within, generalizations can be made about system characteristics necessarily associated with anthropomorphic form and how these interact with the robots' user interfaces. The most useful and important ones identified are related to how the robot moves.

5. Three System Characteristics of Anthropomorphic Robots that Interact with their User Interface

5.1. Intuitive Control

An object that is intuitively controllable by a user is one that may be moved through an arbitrary trajectory with arbitrary change in pose without any additional thought or reflection regarding the movement itself other than that required to move a natural limb. This interface characteristic is most relevant to teleoperators and is illustrated below in terms of a telepresence interface. The processing necessary to achieve this intuitive control was originally done mechanically for the parallel manipulators originally made by Goertz (1954) for the nuclear industry. This type of manipulator was subsequently extended electromechanically to the kinematically matched master-slave manipulators also used in the nuclear industry. It has been implemented repeatedly for a wide variety of systems using variety of digital electronics for systems that were not kinematically matched to human body geometry (Kress, Jansen, Noakes, & Herndon, 1997). In general, intuitive control may be described as resulting in robot motion that is parallel to the input motion produced by the operator, with the operator's torso providing the reference frame of reference.

In all these systems intuitive control is achieved by having the end-effector linearly follow the motion and orientation of the operators' input movement with position control, perhaps with some non-unity gain or a clutching mechanism to allow the operators to episodically disengage control over the end effector. Interestingly, because intuitive manual control is resistant to some nonlinearities, it can be preserved even if a velocity-sensitive gain is introduced, for example, as in the original Apple Macintosh mouse. As will be illustrated by the specific examples of enhancements described below, users' stereoscopic visual system is not as compliant to changes in gain as is their manual control.

In teleoperator or telerobotic systems intuitive manual control also may be achieved through a telepresence control interface (McGreevy & Humphries, 1988) in which the user's hand and head pose is spatially tracked to provide signals that directly control the telerobot's end effectors and viewing direction. The teleoperator illustrated in Figure 5 feeds back to the operator the consequences of his/her control inputs through a variety of sensory displays so that the operator may then plan his/her next action. Telepresence position control contrasts with a velocity control system that could be based on a multi-axis joystick. Telepresence position control can be applied to anthropomorphic as well as nonanthropomorphic systems but the more anthropomorphic the teleoperator device is, the more easily and completely can the telepresence interface be implemented.

One example of how the anthropomorphic form can provide intuitive control is the placement of the robot's cameras with respect to its arms. An anthropomorphic placement of the robot's "head" naturally places the center of camera rotation so as to minimize rotation of the camera's frame of reference with respect to the default control frame of reference for the arms. This design feature greatly assists provision of intuitive control. However, the measurement of relative camera pose totally removes the necessity for anthropomorphic camera placement to achieve intuitive control. The da Vinci[®] surgical teleoperator (Intuitive Surgical, 2015) is the most prominent example that intuitive control can be achieved without exact anthropomorphic placement of a robot's viewing camera with respect to its manipulators.

In the 1980s (when the telepresence concept illustrated in Figure 5 was proposed), many of the incorporated technologies were in an early stage of development. In the interim, these technologies have advanced considerably and, in fact, there are now entire journals dedicated to them, e.g., *Presence* (MIT Press). Regardless, full telepresence systems are still not widely used because of: 1) the physical encumbrance of the sensor suite and motion tracking systems needed to measure body position; 2) the necessity that this tracking be fast and have low latency; and 3) the requirement for accurate, high-fidelity sensory feedback. The pages of *Presence* document progress on all of these issues.

But the concept still faces a basic difficulty in that the hands used as controllers cannot be constantly engaged as position controllers for the teleoperator's limbs. The operators' hands may need, for example, to interact with their immediate physical surroundings to adjust their immediate environmental conditions, e.g., temperature. They may also need to interact with aspects of the teleoperator not involving real-time connection to arm or body position. The operator, for example, may need to use gestures that control the gains and offsets that link their hand positions to those of the teleoperator. The gains and offsets will need to be adjusted from time to time so that the operators may keep their hands in conformable positions with respect to their actual body while still adequately controlling the teleoperator. To do this operators will need a clutching system so they can temporarily disengage their hands from control of the robot limbs.

In the context of teleoperation, a clutching system acts very much like the clutch of a car which disengages and engages the engine's torque from the wheels. A similar function is needed for telepresence control in which the operator's hand position, motion, and shape may be engaged or disengaged from the robot effects they control. The design of such a clutching system is complicated because there are many different degrees of freedom that may be controlled and it is possible that only subsets of them will be engaged or disengaged at any time. For example, the operator may wish to align the teleoperator's head cameras to fixate on a particular view while engaging control of the robots arms and hands. While clutching in the original Virtual Visual Environment Display (VIVED) telepresence concept (McGreevy & Humphries, 1988) was to be under voice control, current implementations of telepresence control will require revisiting this clutching method to compare it to alternatives, trying, for example, techniques analogous to spring-loaded "press to talk" buttons on old fashioned hand-held microphones⁵.

⁵ Jacoby & Ellis (1992) developed and tested an alternative gesture-based clutching system for a menu-driven interface but found it to be inherently awkward because of the frequent mode changes which needed to be signaled by hand gestures.

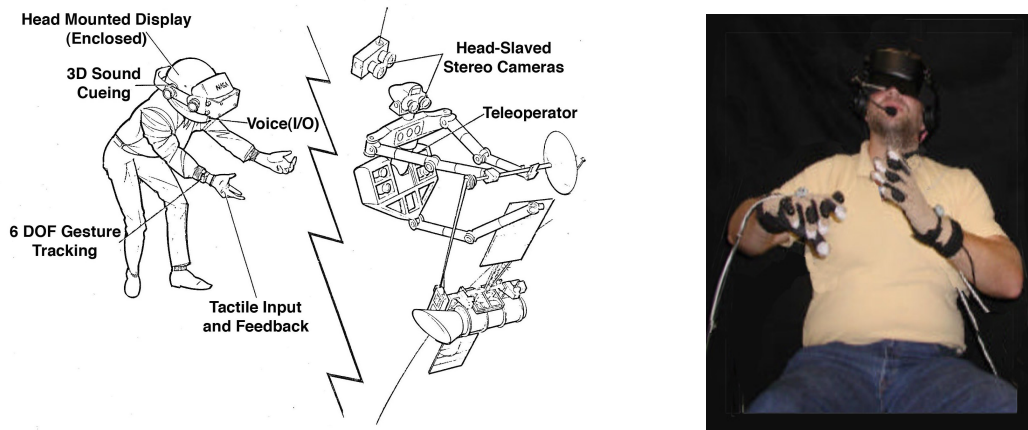


Figure 5. Left: An early concept (VIVED) for a telepresence interface for a space teleoperator. Right: A telepresence control system underdevelopment for Robonaut (after Diftler, Culbert, Ambrose, Platt, & Bluethmann, 2003). The fidelity of the sensory feedback that can be provided by current telepresence display systems has dramatically improved since this conceptual sketch was made (McGreevy & Humphries, 1988). Current visual displays now have much better luminance, resolution, and contrast, e.g., respectively, $>130 \text{ cd/m}^2$, $< 3 \text{ arc-in/pixel}$, and 100:1 (Rockwell-Collins, 2015). 3D sound spatialization systems are available open source (SLAB, 2015). Gesture detection and recognition has been implemented for a wide variety of applications from automatic American Sign Language (Kramer, 1991; Agarwal & Thakur, 2013) to handwriting recognition (Zhai & Kristensson, 2006). Interestingly, the substantial improvements in the telepresence user interface have not been generally connected to the anthropomorphic form of the teleoperator (telerobot) itself. Rather, they have been connected to the improvements in the conceptual and technical fidelity of the displays and controls of the user interface and the general improvements in body position tracking.

Another issue not well recognized associated with telepresence interfaces is that they can require the operator to maintain an elevated hand position for an extended time producing significant muscle fatigue. This problem was encountered years ago by users of the Mattel PowerGloveTM and is not present with joystick-based controllers. One of the often overlooked virtues of a joystick is that it gives the users a convenient place to rest their hands⁶. Despite persisting issues with telepresence interfaces, current development efforts—some at NASA (Ambrose, Aldridge, Askew, Burrige, Bluethman, Diftler, & Lovchik, 2000; Diftler, Ambrose, Joyce, de la Pena, Radford, Parson, Noblitt, 2012)—continue to advance the technology so that it can approach practicality.

Intuitive control is most relevant to low level, position-based interaction with a robot. Once control moves up to the level of velocity control, the most common form for current space teleoperation, more complex thinking than that associated with ordinary human limb movement is required. For example, accomplishing a simple translation movement requires two explicit and different control actions, one to start and a reverse-movement to stop. Consequently, some of the intuitiveness is lost and a classic spring-loaded, center-return joystick becomes a more appropriate control interface.

⁶ Fortunately, the problem with weight is not likely an issue for all space robotics situations since the operator is may be in micro-G. However, the need to be able to engage and disengage control remains because of the awkwardness of having to keep an engaged hand fixed in place to avoid inadvertent robot motion.

Significantly, the direct manipulation techniques of telepresence can be used not just to control a robot but can also be used to plan a possible future position in a system called a predictive display. Such a system was pioneered by Bejczy, Kim and Venema (1990), in which a graphic image of the robot was visually superimposed on the current view of the robot. Their overlay is like a phantom robot that may be controlled to be positioned in the workspace at a potential future position of the real robot. This positioning by the operator is essentially a one step robot program. The software driving the robot may then assess the planned position with respect to a model of the workspace and feedback to the operator the physical consequences of the position that has been chosen. The operator may then adjust the selected position and, when satisfied with it, trigger the movement to the planned position. The actual movement is calculated through inverse kinematics and possibly even inverse dynamics if the forces and velocities of the robot need to be controlled during the movement as well.

Such predictive displays are useful when the robot is very slow or there are time delays much longer than one second. However, intuitive interaction with predictive displays become much more complicated if the operator begins to program a sequence of movements. In this situation a scripting or an outright programming system will need to be added to the direct manipulation technique, especially if the operator wishes to program a sequence of movements contingent on time-varying environmental conditions.

The aforementioned predictive display for robotics is an example of a direct manipulation interface for single-step planning tool. An example of a multi-step tool in which a series future robot positions subject to highly predictable movement and consumable constraint may be planned was the NAVIE system to program multi-burn orbital maneuvers (Grunwald & Ellis, 1993). This planning system illustrates that such systems are very domain specific. They need specific symbology sets for each particular application because the most effective way to present numerical spatial information (e.g., movement constraints) for direct manipulation interfaces is to encode them into specific geometric forms related to task goals. Likewise, if a direct manipulation interface were to be developed for use with a NASA anthropomorphic robot, a detailed study of the movement task, physical constraints, and consumables would be required for each specific implementation to determine the necessary display symbology.

5.2. Sensitivity to Anomalies

One of the long standing issues regarding protracted user surveillance of automated systems is that operators have difficulty maintaining necessary levels of vigilance to detect anomalies that might indicate failures of automation (Coblentz, 1989). This issue would arise primarily when monitoring a fully automated robot, though it is also could be relevant for telerobot operation in move-and-wait mode if there are long latencies between user input and robot response or if the robot is simply very slow.

Anthropomorphic design elements may be used to enhance the salience of movement anomalies in ways that can make them more apparent. The first step is to make the robots move like humans. Robot operators normally develop the ability to detect anomalies in robot movement through extensive training and experience with the robots. However, all users already have such expertise in that humans have especially sensitive abilities to detect deviations from natural human movement (Bidet-Ildei & Orliaguet, 2006). Accordingly, this pre-existing sensitivity can be harnessed by matching normal robots' movement to the kinematic and dynamic patterns of human movement.

Since robot movement anomalies would *ipso facto* be anomalous with respect to familiar normal human motion, discriminability should be increased and the amount of training needed by the crew to detect anomalies would be reduced.

The desired kinematic similarity can be achieved by selecting robot linkages that approximate those of human limbs, necks, and heads. Complete similarity can be achieved if the joint type, linkage, and range of motion of each link are matched to those of the corresponding human limb structure. Achieving dynamic similarity, however, will be more challenging because the movement mechanisms would have to be designed to capture the dynamics of normal human movement. As described in the section of specific enhancements, there are general dynamic features of human movement that can be reproduced by a robot to make the movement human-like. There are also techniques to capture human movement during particular movement tasks in such a way that the movement can be abstracted and played back by a robot so as to appear to be produced by a human (Berg, Miller, Duckworth, Hu, Wan, Fu, Goldberg & Abbeel, 2010, discussed below). Consequently, even robots that are not perfect kinematic matches for human can be trained by contemporary techniques to produce some human-like movement.

5.3. Predictability of Intent

Human operators in charge of monitoring and possibly overriding an automated system may fail to make appropriate commands or issue inappropriate commands because they do not understand the system's current intention. The kind of uncertainty of observers—or even of operators—is reported when the robots execute complex behaviors in a changing environment (Omidshafiei, Agaha, Chen, Ure, How, Vian & Surati, 2015). It can be especially disruptive if a technical failure requires an operator to take over control of a robot that was running autonomously.

There are two different ways anthropomorphic robot techniques can improve operators and companions ability to infer robot intent: 1) to present prominent precursor cues of intentional movement such as gaze direction; and 2) to modify the dynamics of the actual movement itself to make the intent evident from the pattern of motion itself. In fact, there is evidence that human observers naturally use both predictive precursors or dynamic features of movements to infer human agent intent (Ellis & Liston, 2011) and that similar processes are used by humans to infer robot intent (Gielniak & Thomaz, 2011, *et sequela*).

5.3.1 Inferring Intent from Gaze

In the case of human movement, the intent to move can often be recognized by a preceding gaze directed towards the intended target (Neggers & Bekkering, 2001). Similar information could be gleaned from anthropomorphic robots in terms of head pose which can indicate camera direction. Typically, head pose could lead an arm movement but it also could lead movement of the entire robot. Because head pose as estimated by an operator would not be a particularly precise technique for designating of a subsequent movement, an alternative technique is proposed below to enhance this anticipation in a way that could considerably increase the lead time of the prediction.

5.3.2 Inferring Intent from the Movement Itself

The natural human movement dynamics, that can be used to make normal operation more easily discriminable from abnormal movement, can also be used to estimate the likely stopping point of a movement. There is specific evidence that human observers can infer the intent of robot motions before completion of the motion “when motions are familiar” to the observers as natural human

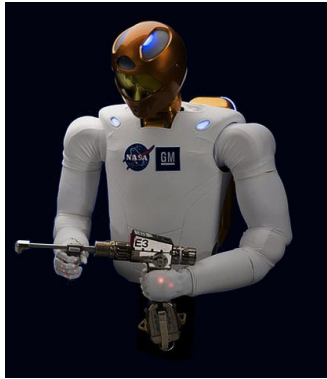
movement (Gielniak & Thomaz, 2011, *et sequelae*). The movement dynamics that make such anticipations possible are undoubtedly the same that make the deviations from familiar human movements more discriminable than similar deviations from unnatural movement (Bidet-Ildi & Orliaguet, 2006). Some of these familiar movement patterns are known with sufficient specificity to allow them to be incorporated into the control laws that drive robots. An example of this dynamic structure is a stopping rule for approaching a target which is discussed in more detail below. In sum, the same phenomenon used to make abnormal behavior more evident can be harnessed to improve operators' and companions' ability to make near-term predictions of robot behavior.

These two examples of features of an anthropomorphic robot, precursors of action or predictive characteristics of the action itself, provide examples of how the anthropomorphic form and motion of the acting robot can serve as kind of natural display that observers or operators can use to predict the future in ways to which they are already accustomed to with respect to other humans. The predictors are in a sense “in the scene” displays in that operators can use them without taking their attention away from the worksite. This characteristic may be a unique feature of anthropomorphic design. A limitation of this type of display, however, is that it may not be sufficiently precise. A remedy for this limitation could be to present additional numerical or symbolic information to supplement the “in the scene display” by the additional information optically overlaid on the operator's worksite view. The information could be presented via a see-through head-mounted display used in “augmented reality” mode, or as suggested below, it could be directly projected optically on the worksite. In either case, standards and guidelines will need to be developed to determine what is sufficient spatial registration for operational use.

6. Why would NASA be Specifically Interested in Anthropomorphic Robots?

NASA's interest in anthropomorphic robots originates in the telepresence interface concept proposed at NASA Ames Research Center in the mid 1980s as well as some early work on hand-like robot end effectors in A. Bejczy's (1990) JPL Telerobotics laboratory. These proposals preceded (and possibly inspired) the Robonaut project. But it is interesting to note that the project was also motivated by the choice to develop a robot that could use existing human space tools because of the considerable investment already made in them and because of the potential for tool sharing during severely mass-constrained exploration missions. This choice and the interest in developing a system that could operate inside as well as outside spacecraft resulted in a number of decisions that led to a robot that evolved to be more anthropomorphic as it was designed to move within spacecraft as crew did. Skin, for example, was added to enclose Robonaut's hands and fingers to protect gripped surfaces from space-glove-damaging gnarling by the grippers. This requirement ended up making the robot even more humanoid and therefore more likely to trigger affective reactions on the part of human companions or operators.

NASA's Robonaut ultimately evolved to an overall form resembling a human's upper torso, head, arms and hands that were able to latch onto standardized rails and other attachment points used in NASA spacecraft (see Figure 6). It was designed to potentially substitute for crew activity inside and outside of spacecraft and eventually to be an assistant working side-by-side with astronauts (Diftler, Ambrose, Joyce, De la Pena, Parsons & Noblitt, 2012). Consequently, Robonaut 1 and 2—which have been constructed as part of a continuing development project—are likely to become more and more anthropomorphic as more experience partnering them with human crew is accumulated.



Robonaut 2 holding a space tool (Diftler et al, 2012).



Electric space drill.



Space “pliers.”

Figure 6. Robonaut 2 with some tools it was designed to use.

The most prominent anthropomorphic element of Robonaut is its head, which houses a pair of stereo cameras with a lateral separation approximating the human interpupillary distance. It uses the cameras to monitor its visual environment, producing a real-time three-dimensional map of the worksite through machine vision and providing stereoscopic feedback to users when in teleoperator mode. The machine vision and human stereoscopic visual information from the camera can be used to guide movement and confirm accomplishment of mechanical tasks in either the fully automatic or teleoperator modes.

Also prominent in Robonaut’s design is the very large number (42) of independent degrees of freedom that may be controlled to mimic human behavior. For example, the arms have a shoulder, elbow, and wrist joints similar to human joints and the degrees of freedom have been assigned in ways to allow the robot to achieve final arm, body, and head poses that resemble those used by human crew for common mechanical reaching, assembly, and grasping tasks. Because of its large number of degrees of freedom, Robonaut is able to accept many robotics tasks resembling human manual manipulation. Its dual end effectors in fact are very similar to a human hand with four fingers and an opposable thumb—potentially giving it very generalized manipulation abilities like a human (Diftler et al, 2012).

Interestingly, Robonaut manipulator design contrasts with the approach taken by Intuitive Surgical for its robot’s end effector, which has no fingers. Instead, the system has many specialized tools (e.g., scissors, hemostats, and a specialized pincher with finger-like functions). All of these attach to the manipulator arm by a special receptacle and give the surgical robot extraordinary dexterity. The performance of the device has been quantitatively well documented with results that show the system gives its operators dexterity approaching that of conventional laparoscopic surgery (Bufano, 2015; Freschi, Ferrari, Melfi, Mosca & Cuschieri, 2012). Consequently, it is reasonable to infer that similar improvements in dexterity and capability could be achieved were specialized tools also to be developed for Robonaut for tasks requiring greater manual dexterity.

The matching of human body kinematics in Robonaut is important because human operators will need not only to control the final hand position and pose but also will need to know the position and

pose of all the links to avoid unwanted collisions. To the extent this matching is correct, operators will be able to use their own intuitive knowledge regarding their own body shape to help keep track of the robots overall position and configuration. This overall body position awareness is especially important during contingency operations during which the crew may have to operate the robot on a less familiar joint-by-joint basis because the normal resolved endpoint control is not working correctly. This type of joint-by-joint control was actually needed for the Remote Manipulator System during the Shuttle mission when Steven Halley first deployed the Hubble Telescope and experienced anomalous robot arm movement (Halley, 1990).

One thing that especially distinguishes Robonaut is not so much the device itself but how it is intended to be used. Because Robonaut can operate in all three of the robot control modes identified by Sheridan (1992), the HARI risk of “Inadequate Design of Human and Automation/Robotic Integration” applies in different ways. For example, in the case of teleoperation, the system risks inadequate design if intuitive control is not provided for manipulation and overall robot movement. In the case of telerobotic control, the risk arises from poor design of short term planning techniques as could be provided by predictive displays. In the case of fully automatic robotic operation, the risk can arise from failure of observers or operators to understand the robot’s current goals and intentions or to notice aberrant behavior that could indicate an incipient failure. Some of the aspects of the risk are, of course, crosscutting and the three characteristics associated with anthropomorphic robots around with this paper is organized can apply in different ways⁷ to all three robot control modes.

7. Enhancements for Anthropomorphic Robot System

This section will describe possible enhancements for anthropomorphic robots in general and specifically for Robonaut in either a teleoperator, telerobot, or fully automatic mode. In general, these enhancements build on some existing anthropomorphic aspect of its design and attempt to improve or create new useful robot performance.

7.1. Using Human Stereo Vision at all Scales

This enhancement will improve human visual inspection resolution, manipulative precision and the declutter function of stereoscopic vision while preserving intuitive control during magnified stereoscopic vision. It will thereby reduce the risk of inadequate design of human-robot interaction.

Robonaut is fitted with sets of paired high-resolution cameras mounted to its head that has three degrees-of-freedom and which rotates in a manner similar to a human head. To the extent that its kinematics match the human neck, the result will be that the image transmitted from the robot back to its operators will generally have an interpretable orientation with respect to the robot’s manipulator arms. Operators “looking through Robonaut’s camera eyes” by viewing panel mounted displays of the images from the robot’s “eyes” will, however, see the image orientation rotate substantially as the robot head is rotated to look around the scene. This illusory rotation occurs because the panel displays are not aligned with the robot’s head frame of reference. One way this problem can be removed is with a telepresence system if the operator uses an orientation-tracked,

⁷ When a telepresence interface is used with a teleoperator, the round-trip communication delay to the teleoperator needs to be well below 20 ms to avoid apparent illusory movement (Ellis, Mania & Adelstein, 2004). This is a much stricter requirement than for most other human-robot interactions.

head-mounted stereoscopic display (HMD) to view the video feeds from the robot's cameras and the tracked orientation of the HMD is used to control the robot's head orientation.

The stereoscopic parameters for the image seen in such a HMD can be appropriate provided the magnification factor of the total imaging system is unity and the inter-camera separation matches the human user's interpupillary separation. If the viewing system is designed to match these two parameters correctly, the user should be able to stereoscopically fuse the left and right images and have useable, depth perception with acceptable eye strain⁸. Stereoscopic viewing is particularly useful for planetary surface exploration because it can provide explorers with a direct sense of depth to nearby surface features, but its often overlooked principal benefit is that of decluttering the users camera view, making it possible to detect small objects that otherwise would be effectively camouflaged.

Like other aspects of an exploration robot, its stereoscopic viewing system of a telepresence display may be designed in an anthropomorphic manner. In fact, selection of a unity overall magnification factor could be considered a natural default for anthropomorphic stereoscopic design. Nonetheless, significant enhancements are possible since it is possible to change the camera magnification as discussed below.

If the robot needed to inspect an object more carefully, it could do so either by moving closer or using zoom to change the system magnification. Because movement to improve the view might be impossible or difficult, magnification change could be the only option available for close inspection. The magnification change, however, has several side effects. Though it increases the effective visual resolution, it also increases the range of stereo disparities within the image, making it hard or even impossible to fuse by the operator. Even if it remains fusible, the resulting image can produce eyestrain or headaches. Another problem that the magnification will produce in a telepresence-based system is one that is exactly like that found when looking through magnifying binoculars: slight head movements cause the entire viewed scene to appear to bounce around.

There are two design modifications that should be introduced to remove these stereo fusion and visual stability problems. First, inter-camera separation should be reduced in proportion to the magnification factor. Ideally, this separation could be under continual control to insure that the range of viewed binocular disparity is always fusible⁹. The second modification would be to reduce the gains of the head tracker so that the head rotations of the telepresence operator produce matched angular rotation of the viewed image. In this way, the benefits of intuitive control can be preserved while Robonaut's head cameras provide a magnified standoff inspection capability that is visually usable directly by the crew. The limiting factor for the amount of attainable magnification would be the jitter in the servo control of the head pointing system and the camera

⁸ A fully natural stereoscopic display would need to present the complete light field (Adelson & Wang, 1992) in order to avoid a mismatch between eye focus and the geometric convergence between the left and right eyes that is present in conventional stereoscopic presentation techniques using paired left and right eye images. This "accommodation-vergence mismatch" is a well-known source of eye strain (Hoffman, Girshick, Akeley & Banks, 2008).

⁹ Additionally, reduction of camera separation to a value less than the human user's eye separation can reduce eye strain by lowering the range of convergence needed for fusion, thus helping to manage the accommodation/vergence mismatch of conventional stereoscopic displays.

separation. However, once the head and cameras were positioned, the servos could be temporarily shut down to eliminate this jitter.

7.2. Moving like a Human

This enhancement will increase the detectability of anomalous motion that could indicate failure or incipient failure. It will also increase the acceptability of robot movement and assist implicit recognition of robot intent. The recognizably human-like movement should reduce training requirements and the risk of unacceptable human performance and should apply to limb and torso movement as well as body translation.

The outward human-like appearance of a robot leads those humans interacting with it either as operators or companions to have expectations that it will move like a human. But even anthropomorphic robots with geometric linkages closely matched to human limbs will not *ipso facto* move like a human. Because of kinematic redundancies, the geometry of any resolved movement path depends strongly on the additional movement constraints and optimization used to determine a path. Consequently, there are significant degrees of design freedom in the selection of criteria to remove the indeterminacy due to the redundancy. These degrees of freedom make it possible to design not just the shape of the robot but the way it moves as well.

The programmed movement of a robot, of course needs to reach its final position and pose. But there are also other aspects of acceptable movement. For example, the movement needs to be smooth enough to confirm normal operation and meet expectations of the operators or companions. But the movement also needs to look right! Strange movements paths that do not resemble those of a human but made by a device resembling a human have been reported to have a kind of “creepy” quality (Rochlis, 2015) that can disturb surrounding observers. Even absolutely correct movement can be grossly, even alarmingly, misinterpreted and disturbing. An anecdotal example illustrates such a misinterpretation.

A mobile robot’s ability to respond to a “Follow Me” command was being tested by a person not involved directly in the system development. The specific behavior was to follow 25 feet behind him. Tracking was based on a video camera system mounted on the vehicle to provide range information. As he started to walk and slowed to look back, the robot correctly followed, slowing to stay 25 feet behind. When he started to walk again, he looked back and speeded up a bit and so did the robot, which had a tight servo on the 25-foot following range. Then he sped up further and the robot sped up too, and so on until the rover’s speed was such that he jumped to the side to get out of the tracking beam. Even though the robot behaved exactly as it was designed to, seeing the robot coming at him so quickly was completely unsettling¹⁰ and the impulse to speed up in this case compounded the problem and seemed dangerously aggressive (Rochlis, 2015).

This anecdote provides an operational example of how motion of a robot under automatic control alone can be sufficient to evoke a strong negative affective response. Increased anthropomorphic form on such a following robot, such as Robonaut torso mounted on a following vehicle, would likely aggravate such a response.

¹⁰ If the person observing the chase were to attribute malice to the rover, this attribution would be an example of high level intentionality, H-intentionality (Admoni & Scassellati, 2012).

Such misinterpretation in specific anticipated situations, of course, can be discouraged by training. But it is also possible for misinterpretations to occur in unanticipated situations, possibly in time critical emergency situations. Accordingly, it is likely worthwhile to determine acceptable starting and stopping behavior for following vehicles to reproduce normal, nonthreatening human following motion to encourage those crew who would physically collaborate with following robots to accept, trust, and use them.

How could a less aggressive movement-stopping rule be selected to avoid the impression that the following robot is hostile? The easiest approach would be to simply slow it down. But this would be inefficient and human motor behavior provides a natural alternative: the dynamic process that leads to Fitts' Law.

Fitts' Law has been shown by Crossman (Crossman & Goodeve, 1983) to arise from a stopping rule in which the moving element makes a series of submovements toward its target with each submovement being a constant proportion of the remaining distance. This process produces a movement with exponentially decreasing speed as the target is approached. Fitts' Law is normally applied to hand movement but is also applies to simple targeting movements of vehicles (Ballou, Burroughs & Ellis, 1997). Moreover, the stopping rule behind Fitts' Law could be more efficient than a uniform deceleration or a simple reduction to a constant slow speed because a vehicle following the rule with the right parameters could move at a higher rate for a greater proportion of the travel distance and yet move slowly at arrival. This type of engineering of robot motion could be applied to limb and torso movement as well as vehicle movement.

But more importantly, Fitts' Law has built in to its dynamics the basis for estimating the actual stopping point in a way familiar to anyone who makes well-practiced, fast, natural human movements. It provides a specific example of how familiarity with the dynamics of human movement can aid operators' ability to predict the goal of a robotic movement. It is interesting to speculate that the poor individual referred to earlier, who thought he was being chased by the robot, would have felt safer if the robot had a slowing or stopping rule reflecting typical human behavior such as Fitts' Law.

It is important to emphasize that the pattern of motion associated with Fitts' Law is only one example of some of the dynamics of human movement that can be used to make robot movement appear natural. In general, research would need to be conducted on the full range of human movement dynamics needed to make robot movement appear natural, acceptable, and safe. Gielnik & Thomaz (2011 *et sequelae*) have done research on the natural appearance of robot movement in the direction of what would be required for motion to be acceptable and appear safe.

There are other advantages to be gained by programming robots, especially anthropomorphic ones, to exhibit normal human biological motion. As noted earlier, research has shown that human observers are especially sensitive to discriminating natural biological motion from unnatural motion (e.g., Bidet-Ildei & Orliaguet, 2006). Robot motion designers can use this fact to increase both the robot operator's and robot companion's sensitivity to off-nominal behavior. The key question would be how can the needed natural human motion patterns be determined for the specific conditions that a space robot might encounter during a mission. One approach to answering this question could be through a principled analysis of the human biodynamics associated with human movements like those the robot would be making. However, this could be quite a detailed task in itself.

An alternative, more direct, approach would be to train a robot to move like a human in the relevant task environments. Such training would not only be helpful to make robot movement more natural and acceptable and thereby make deviations from normal operation more discriminable but it could also provide a path to develop techniques to hand-off work to a robot once a human operator had worked out exactly what needed to be done. Work towards the first of these two approaches has been done at Georgia Tech in the Social Intelligent Machines lab (e.g. Gielniak, Lui & Thomaz, 2013) and work on the second approach has been done with the Berkeley Surgical Robot (Berg, Miller, Duckworth, Hu, Wan, Fu, Goldberg & Abbeel, 2010).

This type of programming by example in which a robot end effector is repeatedly guided by a human trainer through a path that it will subsequently follow is not new. Many industrial robots have been trained in this manner for years. But what is new is to use this technique to train a robot to move in a path that reflects human movement characteristics and which can be abstractly defined so the movement can be implemented in a variety of different geometric positions and at different speeds. Modern techniques appear to now allow the abstraction of the essential characteristics of a path, for example, tying a self-intersecting 3-D path that makes as a specific knot, in such a way that it can generate a variety of exemplars of the path in arbitrary poses. This kind of training has been strikingly demonstrated with the Berkeley Surgical telerobot (Berg, et al, 2010).

The technical specifics of this new technique still need further development to bring it out of the laboratory but it could provide a means to transfer generalized human manual dexterity to robot movement in ways that would be visually acceptable because of its resemblance to actual human movement¹¹. Another aspect of the Berkeley work is that it is explicitly oriented towards developing techniques to hand off work to a robot. First, the human does the movement a few times as a demonstration then the robot “gets” the idea and can continue on its own. Robonaut is an ideal platform for this technique of human-robot training (programming) as it is anthropomorphic and has continuous, intermittent, and fully automatic operational control modes. Research to enable implementation of this robot training by humans will potentially increase the proportion of extravehicular activity (EVA) accomplished by robots reducing risk to crew. Additionally, the training could be reversed in that the robot could be thereafter used to demonstrate manipulative techniques for the crew as part of a crew-training program. In fact, the robot could be thought of as a repository of crew expertise and be used as part of a program by which senior operators transfer their expertise to novices.

7.3. Display of Intent

This enhancement will improve crew ability to sense the intent of a robot’s action through development of a light pointer that will mark the it’s current movement goal directly in the worksite. This technique to explicitly indicate the current movement goal should improve situation awareness, reducing risk of human performance error by replacing inferred prediction with explicit prediction.

The fact that anthropomorphic robots “resemble human form in some way” (Rochlis, 2015) implies that their operators, and especially humans who will work along side them, will inherently expect some human-like behavior. These expectations can be based, for example, on head pose. The robot’s head pose resembles the human gaze direction classically known to precede and predict subsequent movement (Neggers & Bekkering, 2001). Continuous recording and processing of gaze

¹¹ This technique appears to be a next step in training of Robonaut basis behaviors beyond that described by Kawamura (2004).

direction has been, for example, shown to predict human intent during interpersonal interaction (Fiore, Wiltshire, Lobato, Jentsch, Huang & Axelrod, 2013; Huang, Andrist, Sauppé & Mutlu, 2015). Consequently, it should be helpful to use head pose to provide similar intent inferencing aid to humans who will work along side Robonaut. This aid could be provided by improving the directional precision with which they can perceive the robot's head pose, since Robonaut head pose can play the same role as human gaze.

Robot head orientation could function just as human gaze does by temporally leading subsequent movement as typically done by human gaze. But human gaze is more complex and precise than Robonaut head position because it involves both eye-in-head and head rotation. Moreover, because human gaze appears to be used unobtrusively and automatically (Wiese, Wykowska, & Müller, 2013), enhancements to indication of robot gaze indications would by analogy be expected to have minor impact of visual workload.

A highly anthropomorphic way to designate a gaze direction would be to develop moveable eyes for Robonaut to converge onto its current focus of attention, e.g., its movement goal. But a simpler and more effective approach would be to give the robot the ability to project a light ray onto the environmental focus of interest, something like a laser pointer to indicate a current gaze direction (Figure 7). This approach would be more direct, less ambiguous and more obvious to companions than moveable eyes. Information to direct it is already being collected as part of Robonaut's machine vision system. This ray-casting technique would be similar to the light ray cast as an explicit display of system intent already used for mobile robots to inform operators or observers what the robot's current intended goal is (Omidshafiei, Agaha, Chen, Ure, How, Vian & Surati, 2015).

There are several ways the light pointer could be directed. If Robonaut were in teleoperation mode, its operator could manually direct the pointer using visual feedback from the robot's own cameras to determine the spot position. Alternatively, for either continuous or fully automatic mode, Robonaut's existing machine vision system could process the camera images to determine the position and orientation of head-mounted light pointer and the workspace coordinates of the desired illumination point. Thereafter, it could calculate the required pointing angle and direct the pointer and automatically keep it fixated on a point in space designating the intended goal, even though the robot might move its head. For both cases the light pointer would need a pointing mechanism, but it most simply it could be centered in the robot's visual field and directed by head rotations.

Mounting the light pointer on a mobile, reorientable platform such as a Robonaut head necessarily raises questions regarding the stability with which the pointer may be oriented, with problems of occlusion, and with the psychophysical details¹² of the light to be used. The machine vision

¹² Selecting the color, intensity, and duty cycle of the light source for the ray casting represents a significant challenge for this technique of projecting a visible point of light onto a work surface. The dynamic range of background luminance during EVA is enormous. For easy detectability the light needs to be 15% above the background so the system may need an intensity control so as to produce a visible marker during both the light and dark phases. Fortunately, the extremely bright phases of illumination are typically transient (Maida, 2015) and the cast ray can be blinked to improve visibility. If a laser is used, care will need to be taken to avoid hazardous light exposure. Fortunately the EVA helmet visor that is already used during the bright phases of work can provide a convenient protective measure. The situation for IVA use is much less problematic and even a high intensity halogen bulb light pointer may prove adequate, though the luminance will need to be tested in realistic conditions.

system could interactively stabilize the pointer at a designated site location, once one was selected. This kind of stabilized pointing characterizes human gaze and is called “gaze anchoring” (Neggers & Bekkering, 2001) and is another example of human-like movement behavior that the robot could emulate.

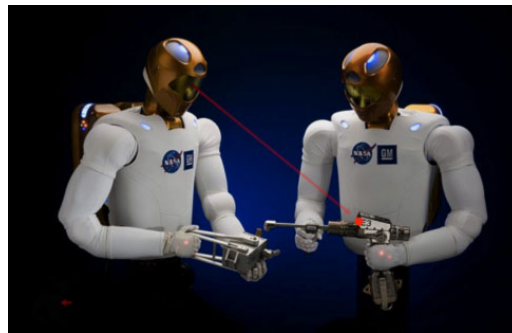


Figure 7. Robonaut with a ray-casting indicator of attention or current goal position. Note that the pointer is just the bright (red) spot not the overlaid arrow showing its location. This image also illustrates the spatial ambiguity of the robots gaze direction if it were indicated only by head position.

8. Final Comments

The anthropomorphic design of Robonaut originally seems to have arisen from an interest in reuse of astronaut tools by robots. This design choice ended up sculpting the entire shape of the robot to have an overall form that resembles a human torso with head and arms. The face of the robot, however, is not particularly humanoid, resembling more the robot from the movie “The Earth Stood Still” than any real human (Wikipedia, 2015). Indeed, an internally animated more realistic face with eyes would likely improve an operator’s or observer’s ability to understand the robots focus of attention.

Because questions naturally arise concerning Robonaut vis-a-vis the state of the art for anthropomorphic robots, it would be interesting to see how well Robonaut would do at a DARPA Robot Challenge. However, since the typical performance environment for Robonaut at the moment is in a micro-G environment, the DARPA test tasks are probably not all appropriate because they are 1-G based. Moreover, Robonaut is not yet really a mobile robot in that it generally grounds itself by attachment.

It is clear one way to assess Robonaut’s performance is to measure how well it can perform on tasks that it is likely to face (Ambrose, Culbert & Frederik, 2001). But limiting its testing to only these does not give a sense how well it might perform in general and does not necessarily provide general information to compare its performance to other anthropomorphic robots. Since there are standard empirical manual dexterity tests¹³ used in Occupational Therapy (Yancosek & Howell, 2009), it would be exceedingly interesting to see how Robonaut and a variety of other anthropomorphic robots do on these tests, if for no other reason to get a sense of how far along their designs are and how far they might be able to go. The example of Intuitive Surgical shows that very great dexterity performance can be achieved though the adaptation of existing special purpose hand tools for direct

¹³ Performance on these Occupational Therapy dexterity tests has been studied with respect to large numbers of individuals to establish population norms and is used to measure manipulative impairment.

connection to their surgical robot. In fact, for practical purposes it could be argued that the da Vinci[®] robot actually provides robot dexterity approaching human manual dexterity¹⁴ (Hubens, Covelier, Balliu & Ruppert, 2003; Bufano, 2015). A parallel increase in dexterity, functionality, and productivity could be awaiting a parallel development with respect to Robonaut.

The fact that Robonaut strikes a significantly human-like pose during operation must influence the opinions and expectations of its operators and observers. As noted by Tondo (2012), the humanoid form itself does skew general expectation about potential robot performance and can influence trust. “Trust is more than experience” (Rochlis, 2015) and can be partially based on expectations independently brought to the worksite based on appearance. But trust is not totally dependent on form. As McDowell (2015) of Intuitive Surgical has commented with respect to the da Vinci[®] robot, its smooth, predictable natural appearing movement is an important factor that increases surgeons’ trust in and acceptance of the system, reinforcing the central conclusion of this paper that anthropomorphic design should go beyond form to also include the design of motion¹⁵.

General Findings

1. Designers of anthropomorphic robots can take advantage of their inherent human-like characteristics to improve user interaction with them in three ways: 1) They can build on the inherent kinematic similarity of the robot’s limbs to design direct manipulation interfaces to give the operators intuitive control over the robots limbs and body position. They can design the various aspects of robots motion to match comparable human movements to 2) improve users’ ability to detect anomalous robot behavior which could signal malfunctions and 3) to enable users to be better able to infer the intent of robot movement.
2. Intuitive control, which generally manifests itself as a direct manipulation user interface, can also be applied to predictive displays designed to compensate for moderate to long time delays in teleoperation and telerobotics. But its full implementation, especially in a telepresence interface such as that which has been proposed for NASA exploration missions, requires research into the specific design of the “clutching” systems for nondisruptive engagement and disengagement of the intuitive control of the motion.
3. The particular benefits for improved anomaly detection and intent inference in anthropomorphic systems depend upon the robot motion kinematically and dynamically resembling normal human motion. Consequently, techniques and methods for capturing natural human motion and transferring it to robots need to be developed. Since natural human motion is highly variable and context dependent, application to NASA tasks will require recording and/or modeling of the specific motions to be executed. In addition to providing trajectories for robot operation, these recordings and models will also be useful for crew training.

¹⁴ However, because use of the da Vinci[®] robot is still high, the cost-benefit trade off does not clearly favor robotic surgery using the system versus a conventional laparoscopic approach (Turchetti, Palla, Pierotte, & Cushier, 2011).

¹⁵ Tondo (2012) reminds that this trust can be misplaced and the benefits of anthropomorphic design for service robots may remain ambiguous. Since the users of service robots typically are not technically sophisticated, the relevance of his finding for NASA robotics is not simple. NASA operators are likely to be specifically trained to be skeptical regarding all human-robotic interaction and may be trained to whatever level of trust is required, though this training itself has an implicit cost.

4. Though anthropomorphic form and natural human motion embodied in these systems can positively affect user acceptance of robots, there appears to be a level of similarity to natural human form and motion at which users can have a strong, negative reaction, a so-called “Uncanny Valley.” This negative reaction is found when the anthropomorphic form and motion is a close match to a human. Consequently, for user acceptance anthropomorphic designs may need to back away from very high fidelity similarity to human form and motion. This caution is an example of the more general observation that anthropomorphic robots can trigger affective reactions in users and observers in ways nonanthropomorphic designs do not.
5. The development of special purpose hand tools and/or special purpose end effectors for Robonaut could likely significantly improve its dexterity and functionality. Consequently, any restriction for it to only be able to use human tools should be relaxed.

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